

Analysis of the 802.11e Enhanced Distributed Channel Access Function [†]

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Abstract

The IEEE 802.11e standard revises the Medium Access Control (MAC) layer of the former IEEE 802.11 standard for Quality-of-Service (QoS) provision in the Wireless Local Area Networks (WLANs). The Enhanced Distributed Channel Access (EDCA) function of 802.11e defines multiple Access Categories (AC) with AC-specific Contention Window (CW) sizes, Arbitration Interframe Space (AIFS) values, and Transmit Opportunity (TXOP) limits to support MAC-level QoS and prioritization. We propose an analytical model for the EDCA function which incorporates an accurate CW, AIFS, and TXOP differentiation at any traffic load. The proposed model is also shown to capture the effect of MAC layer buffer size on the performance. Analytical and simulation results are compared to demonstrate the accuracy of the proposed approach for varying traffic loads, EDCA parameters, and MAC layer buffer space.

I. INTRODUCTION

The IEEE 802.11 standard [1] defines the Distributed Coordination Function (DCF) which provides best-effort service at the Medium Access Control (MAC) layer of the Wireless Local Area Networks (WLANs). The recently ratified IEEE 802.11e standard [2] specifies the Hybrid Coordination Function (HCF) which enables prioritized and parameterized Quality-of-Service (QoS) services at the MAC layer, on top of DCF. The HCF combines a distributed contention-based channel access mechanism, referred to as Enhanced Distributed Channel Access (EDCA), and a centralized polling-based channel access mechanism, referred to as HCF Controlled Channel Access (HCCA).

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We confine our analysis to the EDCA scheme, which uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and slotted Binary Exponential Backoff (BEB) mechanism as the basic access method. The EDCA defines multiple Access Categories (AC) with AC-specific Contention Window (CW) sizes, Arbitration Interframe Space (AIFS) values, and Transmit Opportunity (TXOP) limits to support MAC-level QoS and prioritization [2].

In order to assess the performance of these functions, simulations or mathematical analysis can be used. Although simulation models may capture system dynamics very closely, they lack explicit mathematical relations between the network parameters and performance measures. A number of networking functions would benefit from the insights provided by such mathematical relations. For example, analytical modeling is a more convenient way to assist embedded QoS-aware MAC scheduling and Call Admission Control (CAC) algorithms. Theoretical analysis can provide invaluable insights for QoS provisioning in the WLAN. On the other hand, analytical modeling can potentially be complex, where the effect of multiple layer network parameters makes the task of deriving a simple and accurate analytical model highly difficult. However, a set of appropriate assumptions may lead to simple yet accurate analytical models.

The majority of analytical work on the performance of 802.11e EDCA (and of 802.11 DCF) assumes that every station has always backlogged data ready to transmit in its buffer anytime (in saturation) as will be discussed in Section III. Analysis of the system in this state (saturation analysis) provides accurate and practical asymptotic figures. However, the saturation assumption is unlikely to be valid in practice given the fact that the demanded bandwidth for most of the Internet traffic is variable with significant idle periods. Our main contribution is an accurate EDCA analytical model which releases the saturation assumption. The model is shown to predict EDCA performance accurately for the whole traffic load range from a lightly loaded non-saturated channel to a heavily congested saturated medium for a range of traffic models.

Similarly, the majority of analytical work on the performance of 802.11e EDCA (and of 802.11 DCF) assumes constant collision probability for any transmitted packet at an arbitrary backoff slot independent of the number of retransmissions it has experienced. A complementary assumption is the constant transmission probability for any AC at an arbitrary backoff slot independent of the number of retransmissions it has experienced. As will be discussed in Section III, these approximations lead to accurate analysis in saturation. Our analysis shows that the slot homogeneity assumption leads to accurate performance prediction even when the saturation assumption is released.

Furthermore, the majority of analytical work on the performance of 802.11e EDCA (and of 802.11 DCF) in non-saturated conditions assumes either a very small or an infinitely large MAC layer buffer space. Our analysis removes such assumptions by incorporating the finite size MAC layer queue (interface queue between Link Layer (LL) and MAC layer) into the model. The finite size queue analysis shows the effect of MAC layer buffer space on EDCA performance which we will show to be significant.

A key contribution of this work is that the proposed analytical model incorporates *all* EDCA QoS parameters, CW, AIFS, and TXOP. The model also considers varying collision probabilities at different AIFS slots which is a direct result of varying number of contending stations. Comparing with simulations, we show that our model can provide accurate results for an arbitrary selection of AC-specific EDCA parameters at any load.

We present a Markov model the states of which represent the state of the backoff process and MAC buffer occupancy. To enable analysis in the Markov framework, we assume constant probability of packet arrival per state (for the sake of simplicity, Poisson arrivals). On the other hand, we have also shown that the results also hold for a range of traffic types.

II. EDCA OVERVIEW

The IEEE 802.11e EDCA is a QoS extension of IEEE 802.11 DCF. The major enhancement to support QoS is that EDCA differentiates packets using different priorities and maps them to specific ACs that are buffered in separate queues at a station. Each AC_i within a station ($0 \leq i \leq i_{max}$, $i_{max} = 3$ in [2]) having its own EDCA parameters contends for the channel independently of the others. Following the convention of [2], the larger the index i is, the higher the priority of the AC is. Levels of services are provided through different assignments of the AC specific EDCA parameters; AIFS, CW, and TXOP limits.

If there is a packet ready for transmission in the MAC queue of an AC, the EDCA function must sense the channel to be idle for a complete AIFS before it can start the transmission. The AIFS of an AC is determined by using the MAC Information Base (MIB) parameters as

$$AIFS = SIFS + AIFSN \times T_{slot}, \quad (1)$$

where $AIFSN$ is the AC-specific AIFS number, $SIFS$ is the length of the Short Interframe Space and T_{slot} is the duration of a time slot.

If the channel is idle when the first packet arrives at the AC queue, the packet can be directly transmitted as soon as the channel is sensed to be idle for AIFS. Otherwise, a backoff procedure is completed following

the completion of AIFS before the transmission of this packet. A uniformly distributed random integer, namely a backoff value, is selected from the range $[0, W]$. Should the channel be sensed busy at any time slot during AIFS or backoff, the backoff procedure is suspended at the current backoff value. The backoff resumes as soon as the channel is sensed to be idle for AIFS again. When the backoff counter reaches zero, the packet is transmitted in the following slot.

The value of W depends on the number of retransmissions the current packet experienced. The initial value of W is set to the AC-specific CW_{min} . If the transmitter cannot receive an Acknowledgment (ACK) packet from the receiver in a timeout interval, the transmission is labeled as unsuccessful and the packet is scheduled for retransmission. At each unsuccessful transmission, the value of W is doubled until the maximum AC-specific CW_{max} limit is reached. The value of W is reset to the AC-specific CW_{min} if the transmission is successful, or the retry limit is reached thus the packet is dropped.

The higher priority ACs are assigned smaller AIFSN. Therefore, the higher priority ACs can either transmit or decrement their backoff counters while lower priority ACs are still waiting in AIFS. This results in higher priority ACs enjoying a lower average probability of collision and relatively faster progress through backoff slots. Moreover, in EDCA, the ACs with higher priority may select backoff values from a comparably smaller CW range. This approach prioritizes the access since a smaller CW value means a smaller backoff delay before the transmission.

Upon gaining the access to the medium, each AC may carry out multiple frame exchange sequences as long as the total access duration does not go over a TXOP limit. Within a TXOP, the transmissions are separated by SIFS. Multiple frame transmissions in a TXOP can reduce the overhead due to contention. A TXOP limit of zero corresponds to only one frame exchange per access.

An internal (virtual) collision within a station is handled by granting the access to the AC with the highest priority. The ACs with lower priority that suffer from a virtual collision run the collision procedure as if an outside collision has occurred [2].

III. RELATED WORK

In this section, we provide a brief summary of the theoretical DCF and EDCA function performance analysis in the literature.

The majority of previous work carries out performance analysis for asymptotical conditions assuming each station is in saturation. Three major saturation performance models have been proposed for DCF; *i*) assuming constant collision probability for each station, Bianchi [3] developed a simple Discrete-Time

Markov Chain (DTMC) and the saturation throughput is obtained by applying regenerative analysis to a generic slot time, *ii)* Cali *et al.* [4],[5] employed renewal theory to analyze a p -persistent variant of DCF with persistence factor p derived from the CW, and *iii)* Tay *et al.* [6] instead used an average value mathematical method to model DCF backoff procedure and to calculate the average number of interruptions that the backoff timer experiences. Having the common assumption of slot homogeneity (for an arbitrary station, constant collision or transmission probability at an arbitrary slot), these models define all different renewal cycles all of which lead to accurate saturation performance analysis. Similarly, Medepalli *et al.* [7] provided explicit expressions for average DCF cycle time and system throughput. Pointing out another direction for future performance studies, Hui *et al.* [8] recently proposed the application of metamodeling techniques in order to find approximate closed-form mathematical models.

These major methods are modified by several researchers to include the extra features of the EDCA function in the saturation analysis. Xiao [9],[10] extended [3] to analyze only the CW differentiation. Kong *et al.* [11] took AIFS differentiation into account via a 3-dimensional DTMC. On the other hand, these EDCA extensions miss the treatment of varying collision probabilities at different AIFS slots due to varying number of contending stations. Robinson *et al.* [12],[13] proposed an average analysis on the collision probability for different contention zones during AIFS and employed calculated average collision probability on a 2-dimensional DTMC. Hui *et al.* [14],[15] unified several major approaches into one approximate average model taking into account varying collision probability in different backoff subperiods (corresponds to contention zones in [12]). Zhu *et al.* [16] proposed another analytical EDCA Markov model averaging the transition probabilities based on the number and the parameters of high priority flows. Inan *et al.* [17] proposed a simple DTMC which provides accurate treatment of AIFS and CW differentiation between the ACs for the constant transmission probability assumption. Another 3-dimensional DTMC is proposed by Tao *et al.* [18],[19] in which the third dimension models the state of backoff slots between successive transmission periods. In [18],[19], the fact that the number of idle slots between successive transmissions can be at most the minimum of AC-specific CW_{max} values is considered. Independent from [18],[19], Zhao *et al.* [20] had previously proposed a similar model for the heterogeneous case where each station has traffic of only one AC. Banchs *et al.* [21],[22] proposed another model which considers varying collision probability among different AIFS slots due to a variable number of stations. Chen *et al.* [23], Kuo *et al.* [24], and Lin *et al.* [25] extended [6] in order to include mean value analysis for AIFS and CW differentiation.

Although it has not yet received much attraction, the research that releases the saturation assumption basically follows two major methods; *i*) modeling the non-saturated behavior of DCF or EDCA function via Markov analysis, *ii*) employing queueing theory [26] and calculating certain quantities through average or Markov analysis. Our approach in this work falls into the first category.

Markov analysis for the non-saturated case still assumes slot homogeneity and extends [3] with necessary extra Markov states and transitions. Duffy *et al.* [27] and Alizadeh-Shabdiz *et al.* [28],[29] proposed similar extensions of [3] for non-saturated analysis of 802.11 DCF. Due to specific structure of the proposed DTMCs, these extensions assume a MAC layer buffer size of one packet. We show that this assumption may lead to significant performance prediction errors for EDCA in the case of larger buffers. Cantieni *et al.* [30] extended the model of [28] assuming infinitely large station buffers and the MAC queue being empty with constant probability regardless of the backoff stage the previous transmission took place. Li *et al.* [31] proposed an approximate model for non-saturation where only CW differentiation is considered. Engelstad *et al.* [32] used a DTMC model to perform delay analysis for both DCF and EDCA considering queue utilization probability as in [30]. Zaki *et al.* [33] proposed yet another Markov model with states that are of fixed real-time duration which cannot capture the pre-saturation DCF throughput peak.

A number of models employing queueing theory have also been developed for 802.11(e) performance analysis in non-saturated conditions. These models are assisted by independent analysis for the calculation of some quantities such as collision and transmission probabilities. Tickoo *et al.* [34],[35] modeled each 802.11 node as a discrete time G/G/1 queue to derive the service time distribution, but the models are based on an assumption that the saturated setting provides good approximation for certain quantities in non-saturated conditions. Chen *et al.* [36] employed both G/M/1 and G/G/1 queue models on top of [10] which only considers CW differentiation. Lee *et al.* [37] analyzed the use of M/G/1 queueing model while employing a simple non-saturated Markov model to calculate necessary quantities. Medepalli *et al.* [38] built upon the average cycle time derivation [7] to obtain individual queue delays using both M/G/1 and G/G/1 queueing models. Foh *et al.* [39] proposed a Markov framework to analyze the performance of DCF under statistical traffic. This framework models the number of contending nodes as an $M/E_j/1/k$ queue. Tantra *et al.* [40] extended [39] to include service differentiation in EDCA. However, such analysis is only valid for a restricted scenario where all nodes have a MAC queue size of one packet.

There are also a few studies that investigated the effect of EDCA TXOPs on 802.11e performance for a saturated scenario. Mangold *et al.* [41] and Suzuki *et al.* [42] carried out the performance analysis

through simulation. The efficiency of burst transmissions with block acknowledgements is studied in [43]. Tinnirello *et al.* [44] also proposed different TXOP managing policies for temporal fairness provisioning. Peng *et al.* [45] proposed an analytical model to study the effect of burst transmissions and showed that improved service differentiation can be achieved using a novel scheme based on TXOP thresholds.

A thorough and careful literature survey shows that an EDCA analytical model which incorporates *all* EDCA QoS parameters, CW, AIFS, and TXOP, for *any* traffic load has not been designed yet.

IV. EDCA DISCRETE-TIME MARKOV CHAIN MODEL

Assuming slot homogeneity, we propose a novel DTMC to model the behavior of the EDCA function of any AC at any load. The main contribution of this work is that the proposed model considers the effect of all EDCA QoS parameters (CW, AIFS, and TXOP) on the performance for the whole traffic load range from a lightly-loaded non-saturated channel to a heavily congested saturated medium. Although we assume constant probability of packet arrival per state (for the sake of simplicity, Poisson arrivals), we show that the model provides accurate performance analysis for a range of traffic types.

The state of the EDCA function of any AC at an arbitrary time t depends on several MAC layer events that may have occurred before t . We model the MAC layer state of an AC_i , $0 \leq i \leq 3$, with a 3-dimensional Markov process, $(s_i(t), b_i(t), q_i(t))$. The stochastic process $s_i(t)$ represents the value of the backoff stage at time t , i.e., the number of retransmissions that the packet to be transmitted currently has experienced until time t . The stochastic process $b_i(t)$ represents the state of the backoff counter at time t . Up to this point, the definition of the first two dimensions follows [3] which is introduced for DCF. In order to enable the accurate non-saturated analysis considering EDCA TXOPs, we introduce another dimension which models the stochastic process $q_i(t)$ denoting the number of packets buffered for transmission at the MAC layer. Moreover, as the details will be described in the sequel, in our model, $b_i(t)$ does not only represent the value of the backoff counter, but also the number of transmissions carried out during the current EDCA TXOP (when the value of backoff counter is actually zero).

Using the assumption of independent and constant collision probability at an arbitrary backoff slot, the 3-dimensional process $(s_i(t), b_i(t), q_i(t))$ is represented as a Discrete-Time Markov Chain (DTMC) with states (j, k, l) and index i . We define the limits on state variables as $0 \leq j \leq r_i - 1$, $-N_i \leq k \leq W_{i,j}$ and $0 \leq l \leq Q_{S_i}$. In these inequalities, we let r_i be the retransmission limit of a packet of AC_i ; N_i be the maximum number of successful packet exchange sequences of AC_i that can fit into one TXOP $_i$; $W_{i,j} = 2^{\min(j, m_i)}(CW_{i,\min} + 1) - 1$ be the CW size of AC_i at the backoff stage j where $CW_{i,\max} =$

$2^{m_i}(CW_{i,min} + 1) - 1$, $0 \leq m_i < r_i$; and QS_i be the maximum number of packets that can buffered at the MAC layer, i.e., MAC queue size. Moreover, it is important to note that a couple of restrictions apply to the state indices.

- When there are not any buffered packets at the AC queue, the EDCA function of the corresponding AC cannot be in a retransmitting state. Therefore, if $l = 0$, then $j = 0$ should hold. Such backoff states represent the postbackoff process [1],[2], therefore called as *postbackoff slots* in the sequel. The postbackoff procedure ensures that the transmitting station waits at least another backoff between successive TXOPs. Note that, when $l > 0$ and $k \geq 0$, these states are named *backoff slots*.
- The states with indices $-N_i \leq k \leq -1$ represent the negation of the number of packets that are successfully transmitted at the current TXOP rather than the value of the backoff counter (which is zero during a TXOP). For simplicity, in the design of the Markov chain, we introduced such states in the second dimension. Therefore, if $-N_i \leq k \leq -1$, we set $j = 0$. As it will be clear in the sequel, the addition of these states enables EDCA TXOP analysis.

Let p_{ci} denote the average conditional probability that a packet from AC_i experiences either an external or an internal collision after the EDCA function decides on the transmission. Let $p_{nt}(l', T|l)$ be the probability that there are l' packets in the MAC buffer at time $t + T$ given that there were l packets at t and no transmissions have been made during interval T . Similarly, let $p_{st}(l', T|l)$ be the probability that there are l' packets in the MAC buffer at time $t + T$ given that there were l packets at time t and a transmission has been made during interval T . Note that since we assume Poisson arrivals, the exponential interarrival distributions are independent, and p_{nt} and p_{st} only depend on the interval length T and are independent of time t . Then, the nonzero state transmission probabilities of the proposed Markov model for AC_i , denoted as $P_i(j', k', l'|j, k, l)$ adopting the same notation in [3], are calculated as follows.

- 1) The backoff counter is decremented by one at the slot boundary. Note that we define the postbackoff or the backoff slot as Bianchi defines the slot time [3]. Then, for $0 \leq j \leq r_i - 1$, $1 \leq k \leq W_{i,j}$, and $0 \leq l \leq l' \leq QS_i$,

$$P_i(j, k - 1, l'|j, k, l) = p_{nt}(l', T_{i,bs}|l). \quad (2)$$

It is important to note that the proposed DTMC's evolution is not real-time and the state duration varies depending on the state. The average duration of a backoff slot $T_{i,bs}$ is calculated by (29) which will be derived. Note that, in (2), we consider the probability of packet arrivals during $T_{i,bs}$ (buffer

size l' after the state transition depends on this probability).

2) We assume the transmitted packet experiences a collision with constant probability p_{ci} (slot homogeneity). In the following, note that the cases when the retry limit is reached and when the MAC buffer is full are treated separately, since the transition probabilities should follow different rules. Let $T_{i,s}$ and $T_{i,c}$ be the time spent in a successful transmission and a collision by AC_i respectively which will be derived. Then, for $0 \leq j \leq r_i - 1$, $0 \leq l \leq QS_i - 1$, and $\max(0, l - 1) \leq l' \leq QS_i$,

$$P_i(0, -1, l' | j, 0, l) = (1 - p_{ci}) \cdot p_{st}(l', T_{i,s} | l) \quad (3)$$

$$P_i(0, -1, QS_i - 1 | j, 0, QS_i) = 1 - p_{ci}. \quad (4)$$

For $0 \leq j \leq r_i - 2$, $0 \leq k \leq W_{i,j+1}$, and $0 \leq l \leq l' \leq QS_i$,

$$P_i(j + 1, k, l' | j, 0, l) = \frac{p_{ci} \cdot p_{nt}(l', T_{i,c} | l)}{W_{i,j+1} + 1}. \quad (5)$$

For $0 \leq k \leq W_{i,0}$, $0 \leq l \leq QS_i - 1$, and $\max(0, l - 1) \leq l' \leq QS_i$,

$$P_i(0, k, l' | r_i - 1, 0, l) = \frac{p_{ci}}{W_{i,0} + 1} \cdot p_{st}(l', T_{i,s} | l) \quad (6)$$

$$P_i(0, k, QS_i - 1 | r_i - 1, 0, QS_i) = \frac{p_{ci}}{W_{i,0} + 1} \quad (7)$$

Note that we use p_{nt} in (5) although a transmission has been made. On the other hand, the packet has collided and is still at the MAC queue for retransmission as if no transmission has occurred. This is not the case in (3) and (6), since in these transitions a successful transmission or a drop occurs. When the MAC buffer is full, any arriving packet is discarded as (4) and (7) imply.

3) Once the TXOP is started, the EDCA function may continue with as many packet SIFS-separated exchange sequences as it can fit into the TXOP duration. Let $T_{i,exc}$ be the average duration of a successful packet exchange sequence for AC_i which will be derived in (24). Then, for $-N_i + 1 \leq k \leq -1$, $1 \leq l \leq QS_i$, and $\max(0, l - 1) \leq l' \leq QS_i$,

$$P_i(0, k - 1, l' | 0, k, l) = p_{st}(l', T_{i,exc} | l). \quad (8)$$

When the next transmission cannot fit into the remaining TXOP, the current TXOP is immediately concluded and the unused portion of the TXOP is returned. By design, our model includes maximum

number of packets that can fit into one TXOP. Then, for $0 \leq k \leq W_{i,0}$ and $1 \leq l \leq QS_i$,

$$P_i(0, k, l|0, -N_i, l) = \frac{1}{W_{i,0} + 1}. \quad (9)$$

The TXOP ends when the MAC queue is empty. Then, for $0 \leq k' \leq W_{i,0}$ and $-N_i \leq k \leq -1$,

$$P_i(0, k', 0|0, k, 0) = \frac{1}{W_{i,0} + 1}. \quad (10)$$

Note that no time passes in (9) and (10), so the definition of these states and transitions is actually not necessary for accuracy. On the other hand, they simplify the DTMC structure and symmetry.

4) If the queue is still empty when the postbackoff counter reaches zero, the EDCA function enters the idle state until another packet arrival. Note (0,0,0) also represents the idle state. We make two assumptions; *i*) At most one packet may arrive during T_{slot} with constant probability ρ_i (considering the fact that T_{slot} is in the order of microseconds, the probability that multiple packets can arrive in this interval is very small), *ii*) if the channel is idle at the slot the packet arrives at an empty queue, the transmission will be successful at AIFS completion without any backoff. The latter assumption is due to the following reason. While the probability of the channel becoming busy during AIFS or a collision occurring for the transmission at AIFS is very small at a lightly loaded scenario, the probability of a packet arrival to an empty queue is very small at a highly loaded scenario. As observed via simulations, these assumptions do not lead to any noticeable changes in the results while simplifying the Markov chain structure and symmetry. Then, for $0 \leq k \leq W_{i,0}$ and $1 \leq l \leq QS_i$,

$$P_i(0, 0, 0|0, 0, 0) = (1 - p_{c_i}) \cdot (1 - \rho_i) + p_{c_i} \cdot p_{nt}(0, T_{i,b}|0), \quad (11)$$

$$P_i(0, k, l|0, 0, 0) = \frac{p_{c_i}}{W_{i,0} + 1} \cdot p_{nt}(l, T_{i,b}|0), \quad (12)$$

$$P_i(0, -1, l|0, 0, 0) = (1 - p_{c_i}) \cdot \rho_i \cdot p_{nt}(l, T_{i,s}|0). \quad (13)$$

Let $T_{i,b}$ in (11) and (12) be the length of a backoff slot given it is not idle. Note that actually a successful transmission occurs in the state transition in (13). On the other hand, the transmitted packet is not reflected in the initial queue size state which is 0. Therefore, p_{nt} is used instead of p_{st} .

Parts of the proposed DTMC model are illustrated in Fig. 1 for an arbitrary AC_i with $N_i = 2$. Fig. 1(a) shows the state transitions for $l = 0$. Note that in Fig. 1(a) the states with $-N_i \leq k \leq -2$ can only be reached from the states with $l = 1$. Fig. 1(b) presents the state transitions for $0 < l < QS_i$ and $0 \leq j < r_i$.

Note that only the transition probabilities and the states marked with rectangles differ when $j = r_i - 1$ (as in (6)). Therefore, we do not include an extra figure for this case. Fig. 1(c) shows the state transitions when $l = QS_i$. Note also that the states marked with rectangles differ when $j = r_i - 1$ (as in (7)). The combination of these small chains for all j, k, l constitutes our DTMC model.

A. Steady-State Solution

Let $b_{i,j,k,l}$ be the steady-state probability of the state (j, k, l) of the proposed DTMC with index i which can be solved using (2)-(13) subject to $\sum_j \sum_k \sum_l b_{i,j,k,l} = 1$ (the proposed DTMC is ergodic and irreducible). Let τ_i be the probability that an AC_i transmits at an arbitrary backoff or postbackoff slot

$$\tau_i = \frac{\left(\sum_{j=0}^{r_i-1} \sum_{l=1}^{QS_i} b_{i,j,0,l} \right) + b_{i,0,0,0} \cdot \rho_i \cdot (1 - p_{c_i})}{\sum_{j=0}^{r_i-1} \sum_{k=0}^{W_{i,j}} \sum_{l=0}^{QS_i} b_{i,j,k,l}}. \quad (14)$$

Note that $-N_i \leq k \leq -1$ is not included in the normalization in (14), since these states represent a continuation in the EDCA TXOP rather than a contention for the access. The value of τ_i depends on the values of the average conditional collision probability p_{c_i} , the various state durations $T_{i,bs}$, $T_{i,b}$, $T_{i,s}$ and $T_{i,c}$, and the conditional queue state transition probabilities p_{nt} and p_{st} .

1) *Average conditional collision probability p_{c_i} :* The difference in AIFS of each AC in EDCA creates the so-called *contention zones* as shown in Fig. 2 [12]. In each contention zone, the number of contending stations may vary. The collision probability cannot simply be assumed to be constant among all ACs.

We can define $p_{c_{i,x}}$ as the conditional probability that AC_i experiences either an external or an internal collision given that it has observed the medium idle for $AIFS_x$ and transmits in the current slot (note $AIFS_x \geq AIFS_i$ should hold). For the following, in order to be consistent with the notation of [2], we assume $AIFS_0 \geq AIFS_1 \geq AIFS_2 \geq AIFS_3$. Let $d_i = AIFS_i - AIFS_3$. Also, let the total number AC_i flows be f_i . Then, for the heterogeneous scenario in which each station has only one AC

$$p_{c_{i,x}} = 1 - \frac{\prod_{i':d_{i'} \leq d_x} (1 - \tau_{i'})^{f_{i'}}}{(1 - \tau_i)}. \quad (15)$$

When each station has multiple ACs that are active, internal collisions may occur. Then, for the scenario in which each station has all 4 ACs active

$$p_{c_{i,x}} = 1 - \prod_{i':d_{i'} \leq d_x} (1 - \tau_{i'})^{f_{i'}-1} \prod_{i''>i} (1 - \tau_{i''}). \quad (16)$$

Similar extensions when the number of active ACs are 2 or 3 are straightforward.

We use the Markov chain shown in Fig. 3 to find the long term occupancy of contention zones. Each state represents the n^{th} backoff slot after completion of the AIFS_3 idle interval following a transmission period. The Markov chain model uses the fact that a backoff slot is reached if and only if no transmission occurs in the previous slot. Moreover, the number of states is limited by the maximum idle time between two successive transmissions which is $W_{min} = \min(CW_{i,max})$ for a saturated scenario. Although this is not the case for a non-saturated scenario, we do not change this limit. As the comparison with simulation results show, this approximation does not result in significant prediction errors. The probability that at least one transmission occurs in a backoff slot in contention zone x is

$$p_x^{tr} = 1 - \prod_{i':d_{i'} \leq d_x} (1 - \tau_{i'})^{f_{i'}}. \quad (17)$$

Note that the contention zones are labeled with x regarding the indices of d . In the case of equal AIFS values, the contention zone is labeled with the index of the AC with higher priority.

Given the state transition probabilities as in Fig. 3, the long term occupancy of the backoff slots b'_n can be obtained from the steady-state solution of the Markov chain. Then, the AC-specific average collision probability p_{c_i} is found by weighing zone specific collision probabilities $p_{c_{i,x}}$ according to the long term occupancy of contention zones (thus backoff slots)

$$p_{c_i} = \frac{\sum_{n=d_i+1}^{W_{min}} p_{c_{i,x}} \cdot b'_n}{\sum_{n=d_i+1}^{W_{min}} b'_n} \quad (18)$$

where $x = \max \left(y \mid d_y = \max_z (d_z \mid d_z \leq n) \right)$ which shows x is assigned the highest index value within a set of ACs that have AIFS smaller than or equal to $n + \text{AIFS}_3$. This ensures that at backoff slot n , AC $_i$ has sensed the medium idle for AIFS_x . Therefore, the calculation in (18) fits into the definition of $p_{c_{i,x}}$.

Note that the average collision probability calculation in [12, Section IV-D] is a special case of our calculation for two ACs.

2) *The state duration $T_{i,s}$ and $T_{i,c}$:* Let $T_{i,p}$ be the average payload transmission time for AC $_i$ ($T_{i,p}$ includes the transmission time of MAC and PHY headers), δ be the propagation delay, T_{ack} be the time required for acknowledgment packet (ACK) transmission. Then, for the basic access scheme, we define

the time spent in a successful transmission $T_{i,s}$ and a collision $T_{i,c}$ for any AC_{*i*} as

$$T_{i,s} = T_{i,p} + \delta + SIFS + T_{ack} + \delta + AIFS_i \quad (19)$$

$$T_{i,c} = T_{i,p^*} + ACK_Timeout + AIFS_i \quad (20)$$

where T_{i,p^*} is the average transmission time of the longest packet payload involved in a collision [3]. For simplicity, we assume the packet size to be equal for any AC, then $T_{i,p^*} = T_{i,p}$. Being not explicitly specified in the standards, we set *ACK_Timeout*, using Extended Inter Frame Space (EIFS) as $EIFS_i - AIFS_i$.

The extensions of (19) and (20) for the Request-to-Send/Clear-to-Send (RTS/CTS) scheme are

$$T_{i,s} = T_{rts} + \delta + SIFS + T_{cts} + \delta + SIFS + T_{i,p} + \delta + SIFS + T_{ack} + \delta + AIFS_i \quad (21)$$

$$T_{i,c} = T_{rts} + CTS_Timeout + AIFS_i \quad (22)$$

where T_{rts} and T_{cts} are the time required for RTS and CTS packet transmissions respectively. Being not explicitly specified in the standards, we set *CTS_Timeout* as we set *ACK_Timeout*.

3) *The state duration $T_{i,bs}$ and $T_{i,b}$:* The average time between successive backoff counter decrements is denoted by $T_{i,bs}$. The backoff counter decrement may be at the slot boundary of an idle backoff slot or the last slot of AIFS following an EDCA TXOP or a collision period. We start with calculating the average duration of an EDCA TXOP for AC_{*i*} $T_{i,txop}$ as

$$T_{i,txop} = \frac{\sum_{l=0}^{QS_i} b_{i,0,-N_i,l} \cdot ((N_i - 1) \cdot T_{i,exc} + T_{i,s}) + \sum_{k=-N_i+1}^{-1} b_{i,0,k,0} \cdot ((-k - 1) \cdot T_{i,exc} + T_{i,s})}{\sum_{k=-N_i+1}^{-1} b_{i,0,k,0} + \sum_{l=0}^{QS_i} b_{i,0,-N_i,l}} \quad (23)$$

where $T_{i,exc}$ is defined as the duration of a successful packet exchange sequence within a TXOP. Since the packet exchanges within a TXOP are separated by SIFS rather than AIFS,

$$T_{i,exc} = T_{i,s} - AIFS_i + SIFS, \quad (24)$$

$$N_i = \max(1, \lfloor (TXOP_i + SIFS) / T_{i,exc} \rfloor). \quad (25)$$

Given τ_i and f_i , simple probability theory can be used to calculate the conditional probability of no transmission ($p_{x,i}^{idle}$), only one transmission from AC_{*i*'} ($p_{x,i}^{suc_{i'}}$), or at least two transmissions ($p_{x,i}^{col}$) at the

contention zone x given one AC_i is in backoff.

$$p_{x,i}^{idle} = \begin{cases} \prod_{i':d_{i'} \leq d_x} (1 - \tau_{i'})^{f_{i'}}, & \text{if } d_i > d_x \\ \frac{\prod_{i':d_{i'} \leq d_x} (1 - \tau_{i'})^{f_{i'}}}{1 - \tau_i}, & \text{if } d_i \leq d_x. \end{cases} \quad (26)$$

$$p_{x,i}^{suc_{i'}} = \begin{cases} 0, & \text{if } d_x < d_{i'} \\ f_{i'} \tau_{i'} (1 - \tau_{i'})^{f_{i'} - 1} \prod_{i'':d_{i''} \leq d_x} (1 - \tau_{i''})^{f_{i''}}, & \text{if } d_i > d_x \text{ and } d_{i'} \leq d_x \\ \frac{f_{i'} \tau_{i'} (1 - \tau_{i'})^{f_{i'} - 1}}{1 - \tau_i} \prod_{i'':d_{i''} \leq d_x} (1 - \tau_{i''})^{f_{i''}}, & \text{if } d_i \leq d_x \text{ and } d_{i'} \leq d_x. \end{cases} \quad (27)$$

$$p_{x,i}^{col} = 1 - p_{x,i}^{idle} - \sum_{\forall i'} p_{x,i}^{suc_{i'}} \quad (28)$$

Let x_i be the first contention zone in which AC_i can transmit. Then,

$$T_{i,bs} = \frac{1}{1 - \sum_{\substack{\forall x' \\ x_i < x' \leq 3}} p_{z_{x'}}} \sum_{\forall x'} (p_{x',i}^{idle} \cdot T_{slot} + p_{x',i}^{col} \cdot T_{i,c} + \sum_{\forall i'} p_{x',i}^{suc_{i'}} \cdot T_{i',txop}) \cdot p_{z_{x'}} \quad (29)$$

where p_{z_x} denotes the stationary distribution for a random backoff slot being in zone x . Note that, in (29), the fractional term before summation accounts for the busy periods experienced before AIFS_i is completed. Therefore, if we let $d_{-1} = W_{min}$,

$$p_{z_x} = \sum_{n=d_x+1}^{\min(d_{x'} | d_{x'} > d_x)} b'_n. \quad (30)$$

The expected duration of a backoff slot given it is busy and one AC_i is in idle state is calculated as

$$T_{i,b} = \sum_{\forall x'} \left(\frac{p_{x',i}^{col}}{1 - p_{x',i}^{idle}} \cdot T_{i,c} + \sum_{\forall i'} \frac{p_{x',i}^{suc_{i'}}}{1 - p_{x',i}^{idle}} \cdot T_{i',txop} \right) \cdot p_{z_{x'}}. \quad (31)$$

4) *The conditional queue state transition probabilities p_{nt} and p_{st} :* We assume the packets arrive at the AC queue with size QS_i according to a Poisson process with rate λ_i packets per second. Using the probability distribution function of the Poisson process, the probability of k arrivals occurring in time interval t can be calculated as

$$\Pr(N_{t,i} = k) = \frac{\exp^{-\lambda_i t} (\lambda_i t)^k}{k!}. \quad (32)$$

Then, $p_{nt}(l', T|l)$ and $p_{st}(l', T|l)$ can be calculated as follows. Note that the finite buffer space is considered throughout calculations since the number of packets that may arrive during T can be more than the available queue space.

$$p_{nt}(l', T|l) = \begin{cases} \Pr(N_{T,i} = l' - l), & \text{if } l' < QS_i \\ 1 - \sum_{l'=l}^{QS_i-1} \Pr(N_{T,i} = l' - l), & \text{if } l' = QS_i. \end{cases} \quad (33)$$

$$p_{st}(l', T|l) = \begin{cases} \Pr(N_{T,i} = l' - l + 1), & \text{if } l' < QS_i \\ 1 - \sum_{l'=l-1}^{QS_i-1} \Pr(N_{T,i} = l' - l + 1), & \text{if } l' = QS_i. \end{cases} \quad (34)$$

Note that in (11)-(14), $\rho_i = 1 - \Pr(N_{T,i} = 0)$. Together with the steady-state transition probabilities, (14)-(34) represent a nonlinear system which can be solved using numerical methods.

B. Normalized Throughput Analysis

The normalized throughput of a given AC_i , S_i , is defined as the fraction of the time occupied by the successfully transmitted information. Then,

$$S_i = \frac{p_{s_i} N_{i,txop} T_{i,p}}{p_I T_{slot} + \sum_{i'} p_{s_{i'}} T_{i',txop} + (1 - p_I - \sum_{i'} p_{s_{i'}}) T_c} \quad (35)$$

p_I is the probability of the channel being idle at a backoff slot, p_{s_i} is the conditional successful transmission probability of AC_i at a backoff slot, and $N_{i,txop} = (T_{i,txop} - AIFS_i + SIFS)/T_{i,exc}$. Note that, we consider $N_{i,txop}$ and $T_{i,txop}$ in (35) to define the generic slot time and the time occupied by the successfully transmitted information in the case of EDCA TXOPs.

The probability of a slot being idle, p_I , depends on the state of previous slots. For example, conditioned on the previous slot to be busy ($p_B = 1 - p_I$), p_I only depends on the transmission probability of the ACs with the smallest AIFS, since others have to wait extra AIFS slots. Generalizing this to all AIFS slots, p_I can be calculated as

$$p_I = \sum_{n=0}^{W_{min}} \gamma_n p_B (p_I)^n \cong \sum_{n=0}^{d_0-1} \gamma_n p_B p_I^n + \gamma_{d_0} p_I^{d_0} \quad (36)$$

where γ_n denotes the probability of no transmission occurring at the $(n+1)^{th}$ AIFS slot after $AIFS_3$. Substituting $\gamma_n = \gamma_{d_0}$ for $n \geq d_0$, and releasing the condition on the upper limit of summation, W_{min} , to ∞ , p_I can be approximated as in (36). According to the simulation results, this approximation works

well. Note that $\gamma_n = 1 - p_x^{tr}$ where $x = \max \left(y \mid d_y = \max_z (d_z \mid d_z \leq n) \right)$.

The probability of successful transmission p_{s_i} is conditioned on the states of the previous slots as well. This is again because the number of stations that can contend at an arbitrary backoff slot differs depending on the number of previous consecutive idle backoff slots. Therefore, for the heterogeneous case, in which each station only has one AC, p_{s_i} can be calculated as

$$p_{s_i} = \frac{N_i \tau_i}{(1 - \tau_i)} \left(\sum_{n=d_i+1}^{d_0} \left(p_B p_I^{(n-1)} \prod_{i':0 \leq d_{i'} \leq (n-1)} (1 - \tau_{i'})^{f_{i'}} \right) + (p_I)^{d_0} \prod_{\forall i'} (1 - \tau_{i'})^{f_{i'}} \right). \quad (37)$$

Similarly, for the scenario, in which each station has four active ACs,

$$\begin{aligned} p_{s_i} = & \frac{N_i \tau_i}{(1 - \tau_i)} \left(\sum_{n=d_i+1}^{d_0} \left(p_B p_I^{(n-1)} \prod_{i':0 \leq d_{i'} \leq (n-1)} (1 - \tau_{i'})^{f_{i'}-1} \prod_{i''>i} (1 - \tau_{i''}) \right) \right. \\ & \left. + (p_I)^{d_0} \prod_{\forall i'} (1 - \tau_{i'})^{f_{i'}-1} \prod_{i''>i} (1 - \tau_{i''}) \right). \end{aligned} \quad (38)$$

C. Average Delay Analysis

Our goal is to find total average delay $E[D_i]$ which is defined as the average time from when a packet enters the MAC layer queue of AC_i until it is successfully transmitted. D_i has two components; *i*) queueing time Q_i and *ii*) access time A_i . Q_i is the period that a packet waits in the queue for other packets in front to be transmitted. A_i is the period a packet waits at the head of the queue until it is transmitted successfully (backoff and transmission period). We carry out a recursive calculation as in [11] to find $E[A_i]$ for AC_i . Then, using $E[A_i]$ and $b_{i,j,k,l}$, we calculate $E[D_i] = E[Q_i] + E[A_i]$. Note that, $E[A_i]$ differs depending on whether the EDCA function is idle or not when the packet arrives. We will treat these cases separately. In the sequel, $A_{i,idle}$ denotes the access delay when the EDCA function is idle at the time a packet arrives.

The recursive calculation is carried out in a bottom-to-top and left-to-right manner on the AC-specific DTMC. For the analysis, let $A_i(j, k)$ denote the time delay from the current state (j, k, l) until the packet at the head of the AC_i queue is transmitted successfully ($l \geq 1$). The initial condition on the recursive calculation is

$$A_i(r_i - 1, 0) = T_{i,s}. \quad (39)$$

Recursive delay calculations for $0 \leq j \leq r_i - 1$ are

$$A_i(j, k) = \begin{cases} A_i(j, k - 1) + T_{i,bs}, & \text{if } 1 \leq k \leq W_{i,j} \\ (1 - p_{c_i})T_{i,s} + p_{c_i} \left(\frac{\sum_{k'=0}^{W_{i,j+1}} A_i(j+1, k')}{W_{i,j+1} + 1} + T_{i,c} \right), & \text{if } k = 0 \text{ and } j \neq r_i - 1. \end{cases} \quad (40)$$

Then,

$$E[A_i] = \frac{\sum_{k=0}^{W_{i,0}} A_i(0, k)}{W_{i,0} + 1} \quad (41)$$

Following the assumptions made in (11)-(13) and considering the packet loss probability due to the retry limit as $p_{l,r} = (p_{c_i})^{r_i}$ (note that the delay a dropped packet experiences cannot be considered in a total delay calculation), $E[A_{i,idle}]$ can be calculated as

$$E[A_{i,idle}] = T_{i,s} \cdot (1 - p_{c_i}) + (E[A_i] + T_{i,b}) \cdot p_{c_i} \cdot (1 - p_{l,r}). \quad (42)$$

In this case, the average access delay is equal to the total average delay, i.e., $D_i(0, 0, 0) = E[A_{i,idle}]$.

We perform another recursive calculation to calculate the total delay a packet experiences $D_i(j, k, l)$ (given that the packet arrives while the EDCA function is at state (j, k, l)). In the calculations, we account for the remaining access delay for the packet at the head of the MAC queue and the probability that this packet may be dropped due to the retry limit.

Let $A_{i,d}(j, k)$ be the access delay conditioned that the packet drops. $A_{i,d}(j, k)$ can easily be calculated by modifying the recursive method of calculating $A_i(j, k)$. The initial condition on this recursive calculation is

$$A_{i,d}(r_i - 1, 0) = T_{i,c}. \quad (43)$$

Recursive delay calculations for $0 \leq j \leq r_i - 1$ are

$$A_{i,d}(j, k) = \begin{cases} A_i(j, k - 1) + T_{i,bs}, & \text{if } 1 \leq k \leq W_{i,j} \\ \sum_{k'=0}^{W_{i,j+1}} A_{i,d}(j + 1, k') + T_{i,c}, & \text{if } k = 0 \text{ and } j \neq r_i - 1. \end{cases} \quad (44)$$

Then,

$$E[A_{i,d}] = \frac{\sum_{k=0}^{W_{i,0}} A_{i,d}(0, k)}{W_{i,0} + 1} \quad (45)$$

If a packet arrives during the backoff of another packet, it is delayed at least for the remaining access

time. Depending on the queue size, it may be transmitted at the current TXOP, or may be delayed till further accesses are gained. Then, for $0 \leq j \leq r_i - 1$, $0 \leq k \leq W_{i,j}$, and $1 \leq l \leq QS_i$,

$$\begin{aligned} D_i(j, k, l) = & (1 - p_{l,r}) \cdot (A_i(j, k) + \min(N_i - 1, l - 1) \cdot T_{i,exc} + D_i(-1, -1, l - N_i)) \\ & + p_{l,r} \cdot (A_{i,d}(j, k) + D_i(-1, -1, l - 1)). \end{aligned} \quad (46)$$

When the packet arrives during postbackoff, the total delay is equal to the access delay. Then, for $0 \leq k \leq W_{i,j}$ and $l = 0$,

$$D_i(j, k, l) = A_i(j, k). \quad (47)$$

When the packet arrives during a TXOP, it may be transmitted at the current TXOP, or it may wait for further accesses. Then, for $-N_i + 1 \leq k \leq -1$ and $1 \leq l \leq QS_i$,

$$D_i(j, k, l) = \min(k - 1, l) \cdot T_{i,exc} + D_i(-1, -1, l - k + 1). \quad (48)$$

$D_i(-1, -1, l)$ is calculated recursively according to the value of l

$$D_i(-1, -1, l) = \begin{cases} 0, & \text{if } l \leq 0 \\ E[A_i] \cdot (1 - p_{l,r}), & \text{if } l = 1 \\ \chi, & \text{if } l > 1 \end{cases} \quad (49)$$

where

$$\begin{aligned} \chi = & (1 - p_{l,r}) \cdot (E[A_i] + \min(N_i - 1, l - 1) \cdot T_{i,exc} \\ & + D_i(-1, -1, l - N_i)) + p_{l,r} \cdot (E[A_{i,d}] + D_i(-1, -1, l - 1)). \end{aligned} \quad (50)$$

Let the probability of any arriving packet seeing the EDCA function at state (j, k, l) be $\bar{b}_{i,j,k,l}$. Since we assume independent and exponentially distributed packet interarrivals, $\bar{b}_{i,j,k,l}$ can simply be calculated by normalizing $b_{i,j,k,l}$ excluding the states in which no time passes, i.e., $\forall(j, k, l)$ such that $(0, -N_i, 1 \leq l \leq QS_i)$ or $(0, -N_i \leq k \leq -1, 0)$. Note that $\bar{b}_{i,j,k,l}$ is zero for these states

$$\bar{b}_{i,j,k,l} = \frac{b_{i,j,k,l}}{1 - \sum_{l=1}^{QS_i} b_{i,0,-N_i,l} - \sum_{k=-N_i}^{-1} b_{i,0,k,0}}. \quad (51)$$

Then, the total average delay a successful packet experiences $E[D_i]$ can be calculated averaging $D_i(j, k, l)$

over all possible states

$$E[D_i] = E[A_{i,idle}] \cdot \bar{b}_{i,0,0,0} + \sum_{\forall(j,k,l)/(0,0,0)} D_i(j, k, l) \cdot \bar{b}_{i,j,k,l}. \quad (52)$$

D. Average Packet Loss Ratio

We consider two types of packet losses; *i*) the packet is dropped when the MAC layer retry limit is reached, *ii*) the packet is dropped if the MAC queue is full at the time of packet arrival. Let plr_i denote the average packet loss ratio for AC_i . We use the steady-state probability $b_{i,j,k,l}$ to find the probability whether the MAC queue is full or not at the time of packet arrival. If the queue is full, the arriving packet is dropped (second term in (53)). Otherwise, the packet is dropped with probability $p_{c_i}^{r_i}$, i.e. only if the retry limit is reached (first term in (53)). Note that we consider packet retransmissions only due to packet collisions. Then,

$$plr_i = \sum_{j=0}^{r_i-1} \sum_{k=0}^{W_{i,j}} \sum_{l=0}^{QS_i-1} b_{i,j,k,l} \cdot p_{c_i}^{r_i} + \sum_{j=0}^{r_i-1} \sum_{k=0}^{W_{i,j}} b_{i,j,k,QS_i}. \quad (53)$$

E. Queue Size Distribution

Due to the specific structure of the proposed model, it is straightforward to calculate the MAC queue size distribution for AC_i . Note that we use queue size distribution in the calculation of average packet loss ratio.

$$\Pr(l = l') = \sum_{j=0}^{r_i-1} \sum_{k=0}^{W_{i,j}} b_{i,j,k,l'}. \quad (54)$$

V. NUMERICAL AND SIMULATION RESULTS

We validate the accuracy of the numerical results calculated via the proposed EDCA model by comparing them with the simulations results obtained from ns-2 [46]. For the simulations, we employ the IEEE 802.11e HCF MAC simulation model for ns-2.28 that we developed [47]. This module implements all the EDCA and HCCA functionalities stated in [2].

As in all work on the subject in the literature, we consider ACs that transmit fixed-size User Datagram Protocol (UDP) packets. In simulations, we consider two ACs, one high priority and one low priority. Each station runs only one traffic class. Unless otherwise stated, the packets are generated according to a Poisson process with equal rate for both ACs. We set $AIFSN_1 = 3$, $AIFSN_3 = 2$, $CW_{1,min} = 15$, $CW_{3,min} = 7$, $m_1 = m_3 = 3$, $r_1 = r_3 = 7$. For both ACs, the payload size is 1034 bytes. Again, as in most of the work on the subject, the simulation results are reported for the wireless channel which is

assumed to be not prone to any errors during transmission. The errored channel case is left for future study. All the stations have 802.11g Physical Layer (PHY) using 54 Mbps and 6 Mbps as the data and basic rate respectively ($T_{slot} = 9 \mu s$, $SIFS = 10 \mu s$) [48]. The simulation runtime is 100 seconds.

Fig. 4 shows the differentiation of throughput for two ACs when EDCA TXOP limits of both are set to 0 (1 packet exchange per EDCA TXOP). In this scenario, there are 5 stations for both ACs and they are transmitting to an AP. The normalized throughput per AC as well as the total system throughput is plotted for increasing offered load per AC. We have carried out the analysis for maximum MAC buffer sizes of 2 packets and 10 packets. The comparison between analytical and simulation results shows that our model can accurately capture the linear relationship between throughput and offered load under low loads, the complex transition in throughput between under-loaded and saturation regimes, and the saturation throughput. Although we do not present here, considerable inaccuracy is observed if the postbackoff procedure, varying collision probability among different AIFS zones, and varying service time among different backoff stages are not modeled correctly as proposed. The results also present that the slot homogeneity assumption works accurately in a non-saturated model for throughput estimation.

The proposed model can also capture the throughput variation with respect to the size of the MAC buffer. The results reveal how significantly the size of the MAC buffer affects the throughput in the transition period from underloaded to highly loaded channel. This also shows small interface buffer assumptions of previous models [27],[28],[29],[40] can lead to considerable analytical inaccuracies. Although the total throughput for the small buffer size case has higher throughput in the transition region for the specific example, this cannot be generalized. The reason for this is that AC_1 suffers from low throughput for $QS_1 = 10$ due to the selection of EDCA parameters, which affects the total throughput.

It is also important to note that the throughput performance does not differ significantly (around %1-%2) for buffer sizes larger than 10 packets for the given scenarios. Therefore, we do not include such cases in order not to complicate the figures. Since the complexity of the mathematical solution increases with the increasing size of the third dimension of DTMC, it may be preferable to implement the model for smaller queue sizes when the throughput performance is not expected to be affected by the selection.

Fig. 5 depicts the differentiation of throughput for two ACs when EDCA TXOP limits are set to 1.504 ms and 3.008 ms for high and low priority ACs respectively. For TXOP limits, we use the suggested values for voice and video ACs in [2]. It is important to note that the model works for an arbitrary selection of the TXOP limit. According to the selected TXOP limits, $N_1 = 5$ and $N_2 = 11$. The normalized throughput per

AC as well as the total system throughput is plotted while increasing offered load per AC. We have done the analysis for maximum MAC buffer sizes of 2 packets and 10 packets. The model accurately captures the throughput for any traffic load. As expected, increasing maximum buffer size to 10 packets increases the throughput both in the transition and the saturation region. Note that when more than a packet fits into EDCA TXOPs, this decreases contention overhead which in turn increases channel utilization and throughput (comparison of Fig. 5 with Fig. 4). Although corresponding results are not presented here, the model works accurately for higher queue sizes in the case of EDCA TXOPs as well.

Fig. 6 displays the differentiation of throughput for two ACs when packet arrival rate is fixed to 2 Mbps and the station number per AC is increased. We have done the analysis for the MAC buffer size of 10 packets with EDCA TXOPs enabled. The analytical and simulation results are well in accordance. As the traffic load increases, the differentiation in throughput between the ACs is observed.

Fig. 7 shows the normalized throughput for two ACs when offered load per AC is not equal. In this scenario, we set the packet arrival rate per AC_1 to 2 Mbps and the packet arrival rate per AC_3 to 0.5 Mbps. The analytical and simulation results are well in accordance. As the traffic load increases, AC_3 maintains linear increase with respect to offered load, while AC_1 experiences decrease in throughput due to larger settings of AIFS and CW if the total number of stations exceeds 22.

In the design of the model, we assume constant packet arrival probability per state. The Poisson arrival process fits this definition because of the independent exponentially distributed interarrival times. We have also compared the throughput estimates obtained from the analytical model with the simulation results obtained using an On/Off traffic model in Fig. 8. A similar study has first been made for DCF in [27]. We modeled the high priority with On/Off traffic model with exponentially distributed idle and active intervals of mean length 1.5 s. In the active interval, packets are generated with Constant Bit Rate (CBR). The low priority traffic uses Poisson distributed arrivals. Note that we leave the packet size unchanged, but normalize the packet arrival rate according to the on/off pattern so that total offered load remains constant to have a fair comparison. The analytical predictions closely follow the simulation results for the given scenario. We have observed that the predictions are more sensitive if the transition region is entered with a few number of stations (5 stations per AC).

Our model also provides a very good match in terms of the throughput for CBR traffic. In Fig. 9, we compare the throughput prediction of the proposed model with simulations using CBR traffic. The packet arrival rate is fixed to 2 Mbps for both ACs and the station number per AC is increased. MAC buffer size

is 10 packets and EDCA TXOPs are enabled.

Fig. 10 depicts the total average packet delay with respect to increasing traffic load per AC. We present the results for two different scenarios. In the first scenario, TXOP limits are set to 0 ms for both ACs. In the second scenario, TXOP limits are set to 1.504 ms and 3.008 ms for high and low priority ACs respectively. The analysis is carried out for a buffer size of 10 packets. As the results imply, the analytical results closely follow the simulation results for both scenarios. In the lightly loaded region, the delays are considerably small. The increase in the transition region is steeper when TXOP limits are 0. In the specific example, enabling TXOPs decreases the total delay where the decrease is more considerable for the low priority AC (due to selection of parameters). Since the buffer size is limited, the total average delay converges to a specific value as the load increases. Still this limit is not of interest, since the packet loss rate at this region is unpractically large. Note that this limit will be higher for larger buffers. The region of interest is the start of the transition region (between 2 Mbps and 3 Mbps for the example in Fig. 10). On the other hand, we also display other data points to show the performance of the model for the whole load span.

Fig. 11 depicts the average packet loss ratio with respect to increasing traffic load per AC. We present the results for two different scenarios. In the first scenario, TXOP limits are set to 0 ms for both ACs. In the second scenario, TXOP limits are set to 1.504 ms and 3.008 ms for high and low priority ACs respectively. The analysis is carried out for a buffer size of 10 packets. As the results imply, the analytical results closely follow the simulation results for both scenarios. Although it is not presented in Fig. 11, the packet loss ratio drops exponentially to 0 when the offered load per AC is lower than 2.5 Mbps.

The results presented in this paper fixes the AIFS and CW parameters for each AC. The results are compared for different TXOP values at varying traffic load. Therefore, the presented results can mainly indicate the effects of TXOP on the maximum throughput. The model can also be used in order to investigate the effects of AIFS and CW on the maximum throughput.

As the comparison of Fig. 4 and Fig. 5 reveals, the total throughput can be maximized with the introduction of EDCA TXOPs which enable multiple frame transmissions in one channel access (note that MAC buffer sizes for each AC should be equal to or larger than the number of packets that can fit to the AC-specific TXOP in order to efficiently utilize each TXOP gained). EDCA TXOPs decrease the channel contention overhead and the ACs can efficiently utilize the resources. Note also that the effects of EDCA TXOPs in the lightly loaded region is marginal compared to highly loaded region. This is expected

since the MAC queues do not build up in the lightly loaded scenario where stations usually have just one packet to send at their access to the channel.

As Fig. 4 shows the saturation throughput is usually less than the maximum throughput that can be obtained. This is also observed for DCF in [3]. Similarly, in Fig. 6-Fig. 9, the total throughput slightly decreases as the total load increases. As the load in the system increases the collision overhead becomes significant which decreases the total channel utilization. On the other hand, as also discussed in [3], the point where the maximum throughput is observed is unstable in a random access system. Therefore, a good admission control algorithm should be defined to operate the system at the point right before the lightly loaded to highly loaded transition region starts.

VI. CONCLUSION

We have presented an accurate Markov model for analytically calculating the EDCA throughput and delay for the whole traffic load range from a lightly loaded non-saturated channel to a heavily congested saturated medium. The presented model shows the accuracy of the homogeneous slot assumption (constant collision and transmission probability at an arbitrary backoff slot) that is extensively studied in saturation scenarios for the whole traffic range. The presented model accurately captures the linear relationship between throughput and offered load under low loads and the limiting behavior of throughput at saturation.

The key contribution of this paper is that the model accounts for all of the differentiation mechanisms EDCA proposes. The analytical model can incorporate any selection of AC-specific AIFS, CW, and TXOP values for any number of ACs. The model also considers varying collision probabilities at different contention zones which provides accurate AIFS differentiation analysis. Although not presented explicitly in this paper, it is straightforward to extend the presented model for scenarios where the stations run multiple ACs (virtual collisions may take place) or RTS/CTS protection mechanism is used. The approximations made for the sake of DTMC simplicity and symmetry may also be removed easily for increased accuracy, although they are shown to be highly accurate.

We also show that the MAC buffer size affects the EDCA performance significantly between underloaded and saturation regimes (including saturation) especially when EDCA TXOPs are enabled. The presented model captures this complex transition accurately. This analysis also points out the fact that including an accurate queue treatment is vital. Incorporating MAC queue states also enables EDCA TXOP analysis so that the EDCA TXOP continuation process is modeled in considerable detail. To the authors' knowledge this is the first demonstration of an analytic model including EDCA TXOP procedure for finite load.

It is also worth noting that our model can easily be simplified to model DCF behavior. Moreover, after modifying our model accordingly, the throughput analysis for the infrastructure WLAN where there are transmissions both in the uplink and downlink can be performed (note that in a WLAN downlink traffic load may significantly differ from uplink traffic load).

Although the Markov analysis assumes the packets are generated according to Poisson process, the comparison with simulation results shows that the throughput analysis is valid for a range of traffic types such as CBR and On/Off traffic (On/Off traffic model is a widely used model for voice and telnet traffic).

The non-existence of a closed-form solution for the Markov model limits its practical use. On the other hand, the accurate saturation throughput analysis can highlight the strengths and the shortcomings of EDCA for varying scenarios and can provide invaluable insights. The model can effectively assist EDCA parameter adaptation or a call admission control algorithm for improved QoS support in the WLAN.

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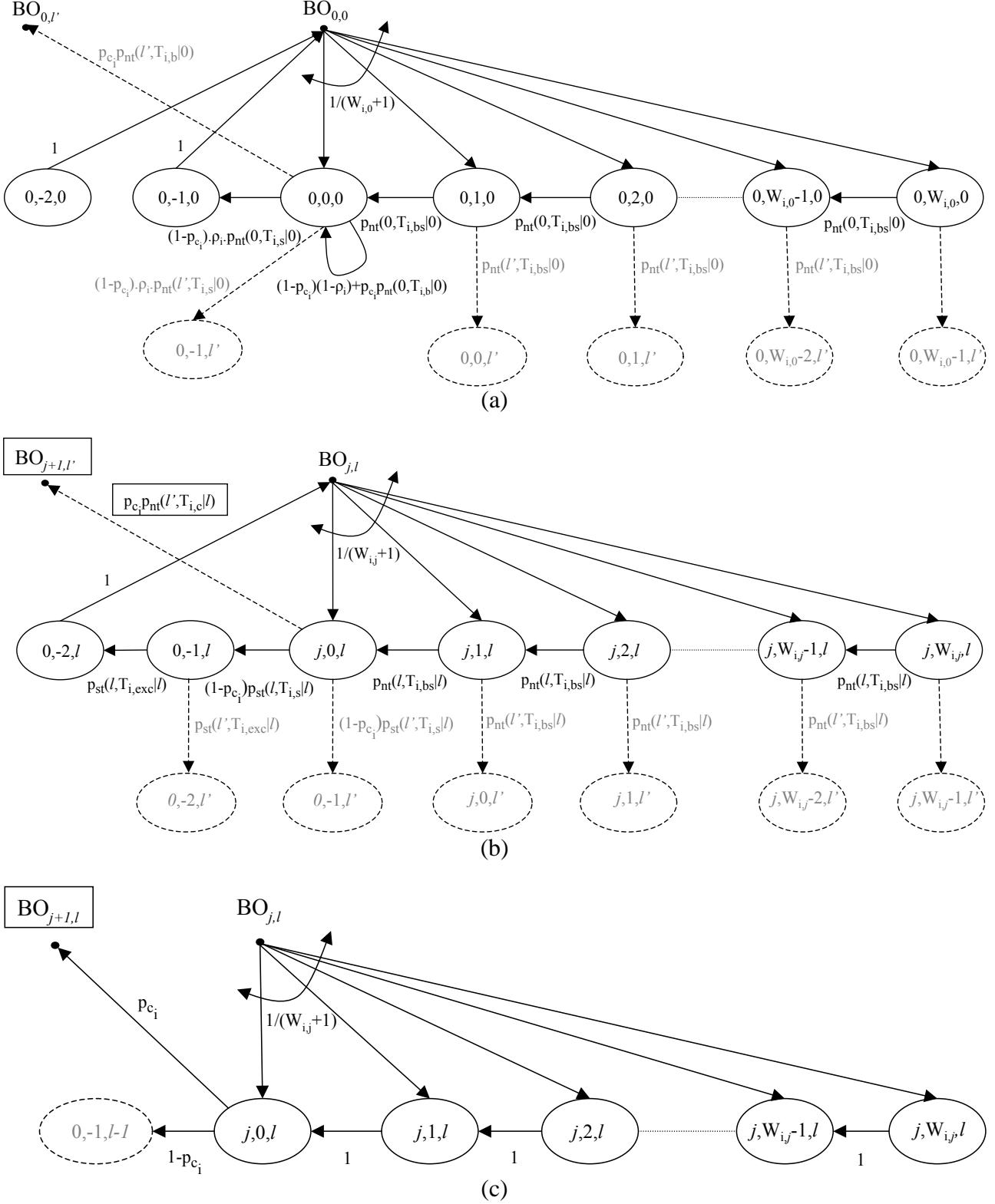


Fig. 1. Parts of the proposed DTMC model for $N_i=2$. The combination of these small chains for all j, k, l constitutes the proposed DTMC model. (a) $l=0$. (b) $0 < l < Q_Si$. (c) $l = Q_Si$. Remarks: i) the transition probabilities and the states marked with rectangles differ when $j = r_i - 1$ (as in (6) and (7)), ii) the limits for l' follow the rules in (2)-(13).

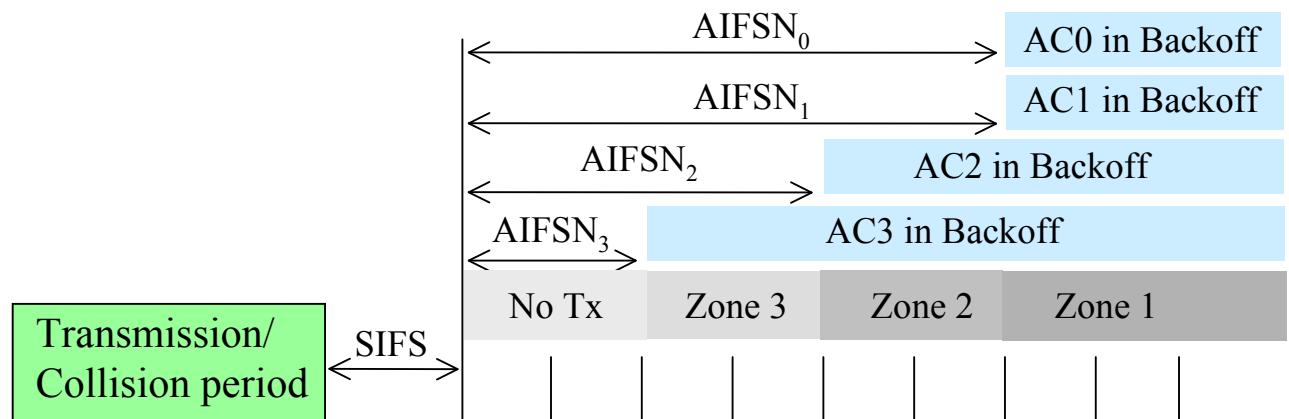


Fig. 2. EDCA backoff after busy medium.

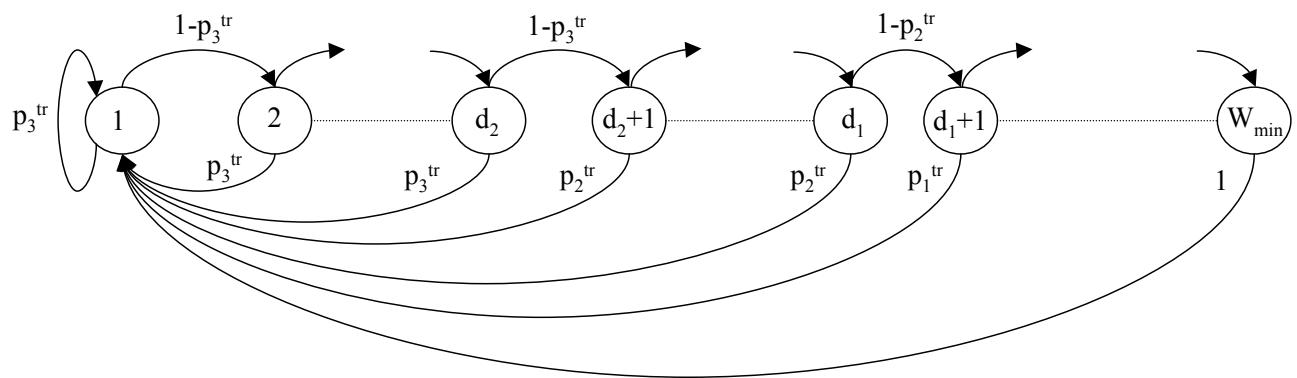


Fig. 3. Transition through backoff slots in different contention zones for the example given in Fig.2.

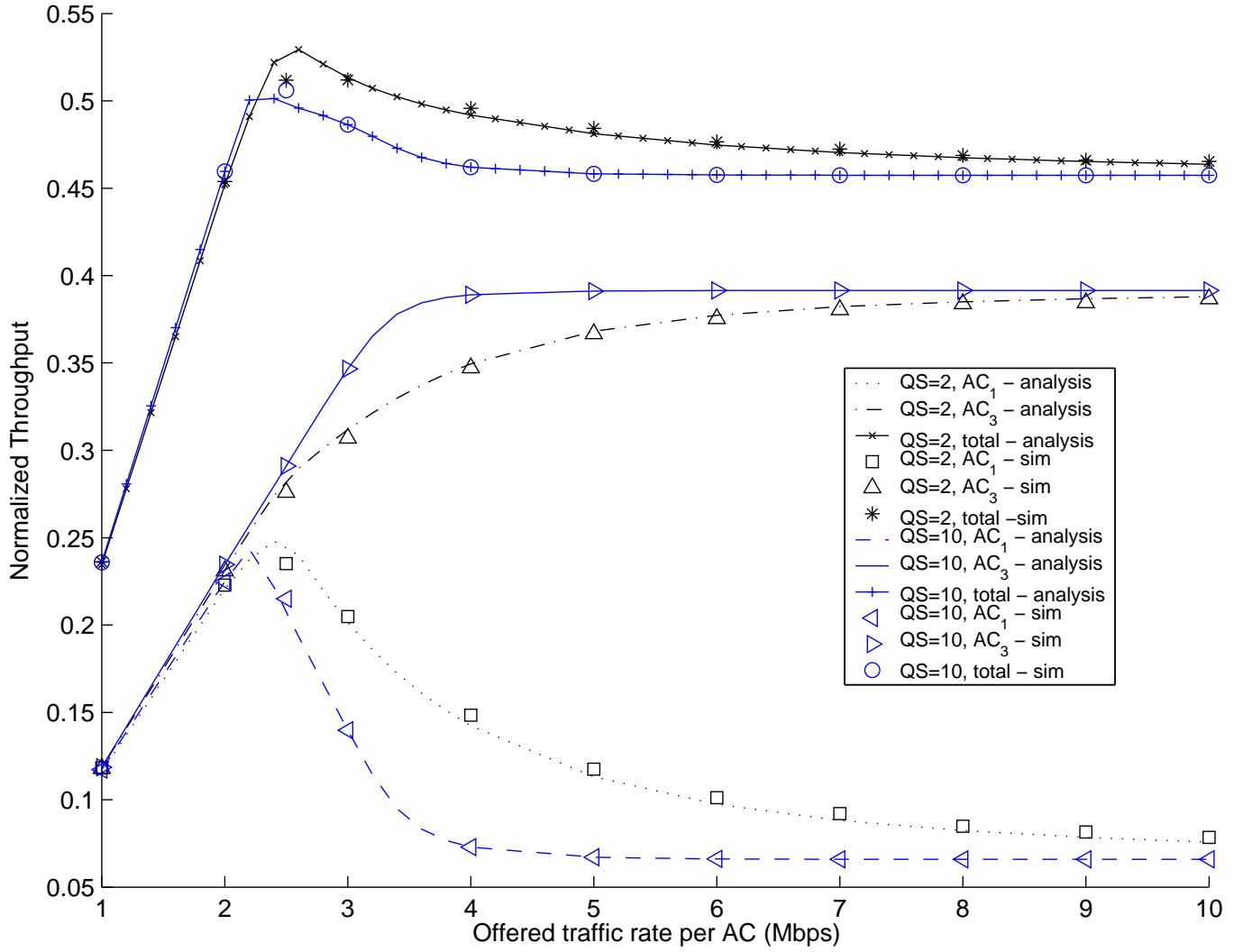


Fig. 4. Normalized throughput prediction of the proposed model for 2 AC heterogeneous scenario with respect to increasing load per AC at each station and varying MAC buffer size in basic access mode ($TXOP_3 = 0$, $TXOP_1 = 0$). Simulation results are also added for comparison.

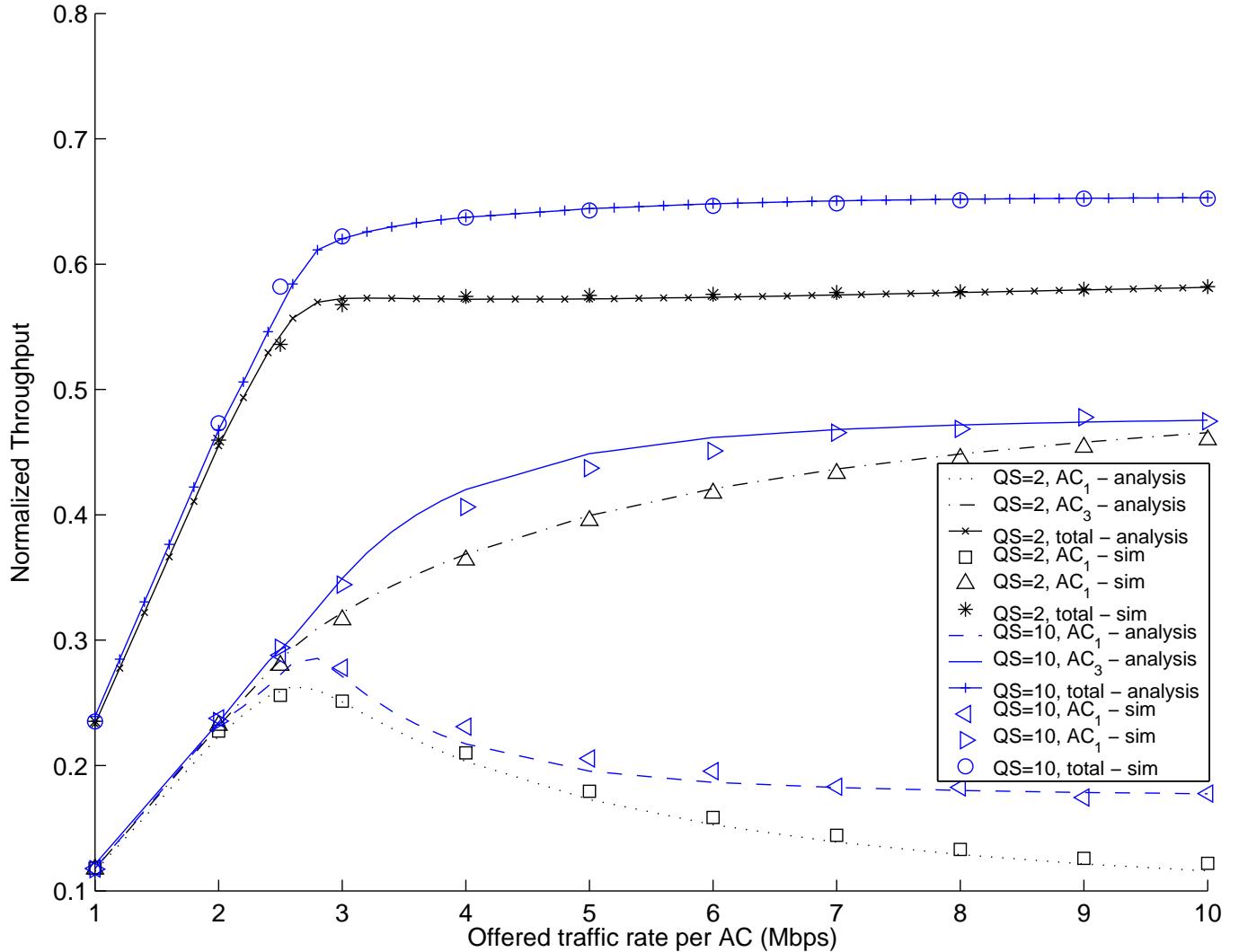


Fig. 5. Normalized throughput prediction of the proposed model for 2 AC heterogeneous scenario with respect to increasing load per AC at each station and varying MAC buffer size in basic access mode ($TXOP_3 = 1504ms$, $TXOP_1 = 3008ms$). Simulation results are also added for comparison.

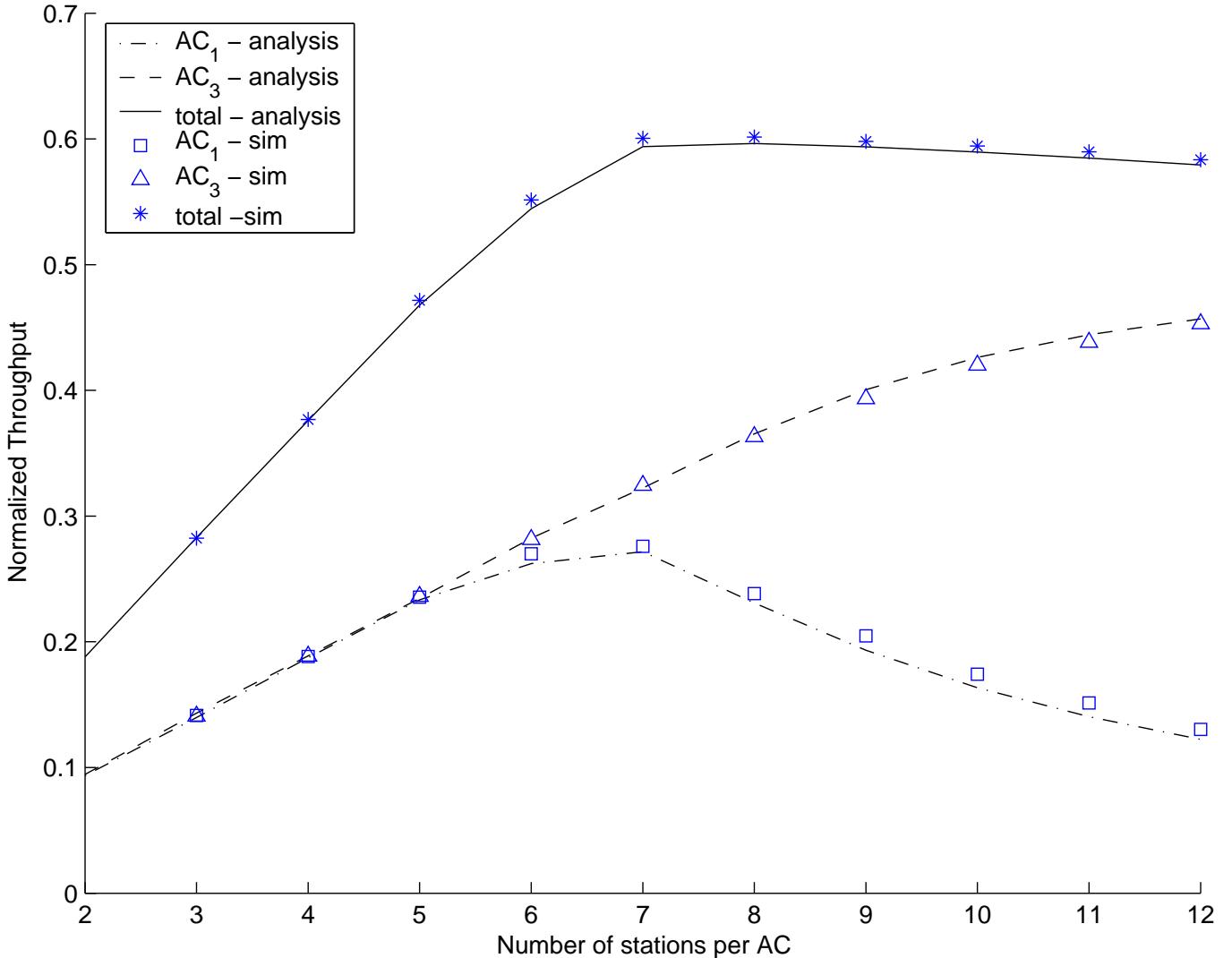


Fig. 6. Normalized throughput prediction of the proposed model for 2 AC heterogeneous scenario with respect to increasing number of stations when MAC buffer size is 10 packets and total offered load per AC is 2 Mbps ($TXOP_3 = 1504ms$, $TXOP_1 = 3008ms$). Simulation results are also added for comparison.

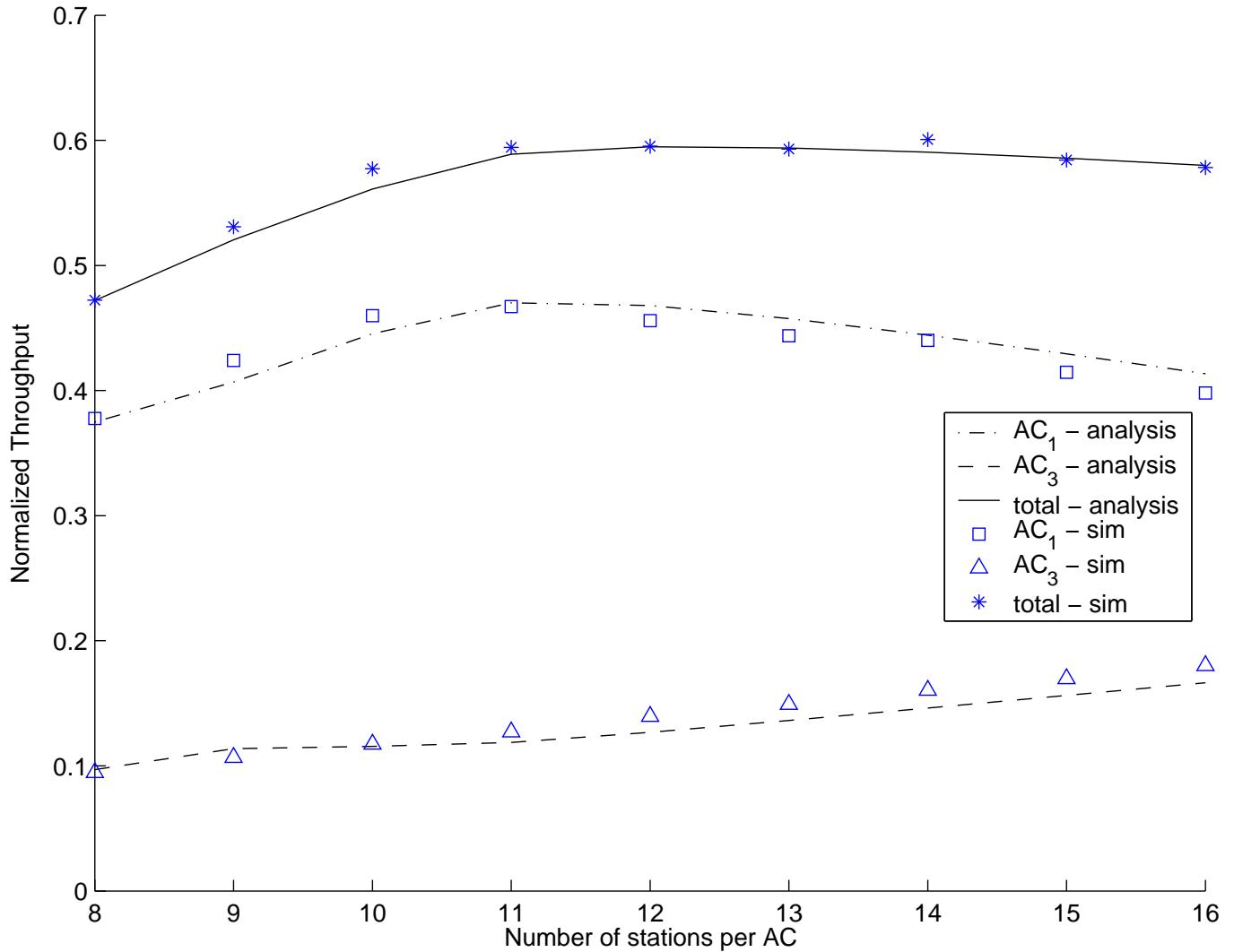


Fig. 7. Normalized throughput prediction of the proposed model for 2 AC heterogeneous scenario with respect to increasing number of stations when MAC buffer size is 10 packets ($TXOP_3 = 1504ms$, $TXOP_1 = 3008ms$). Total offered load per AC_3 is 0.5 Mbps while total offered load per AC_3 is 2 Mbps. Simulation results are also added for comparison.

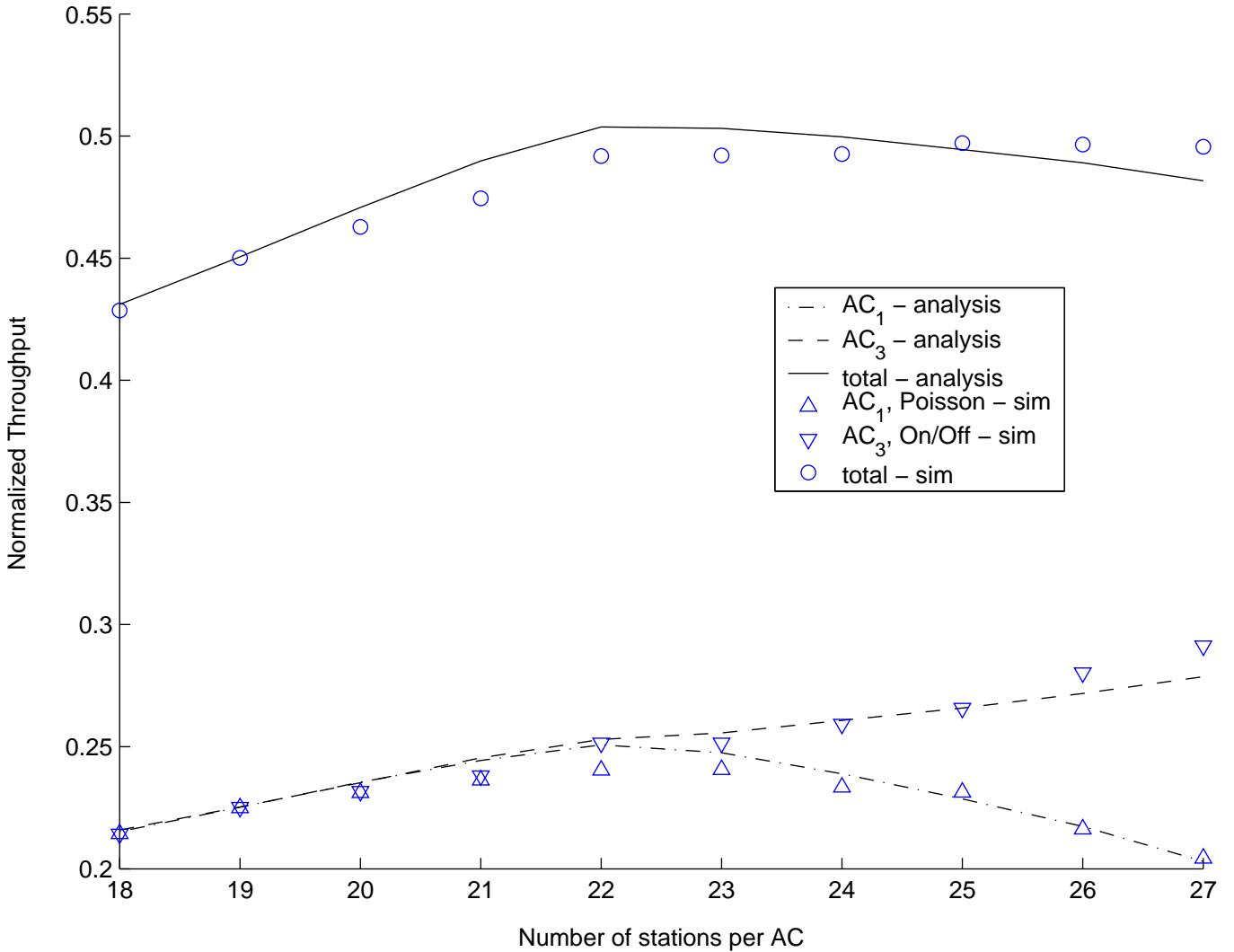


Fig. 8. Normalized throughput prediction of the proposed model for 2 AC heterogeneous scenario with respect to increasing number of stations when total offered load per AC is 0.5 Mbps ($TXOP_3 = 1504ms$, $TXOP_1 = 3008ms$). Simulation results are also added for the scenario when AC_3 uses On/Off traffic with exponentially distributed idle and active times both with mean 1.5s. AC_1 uses Poisson distribution for packet arrivals.

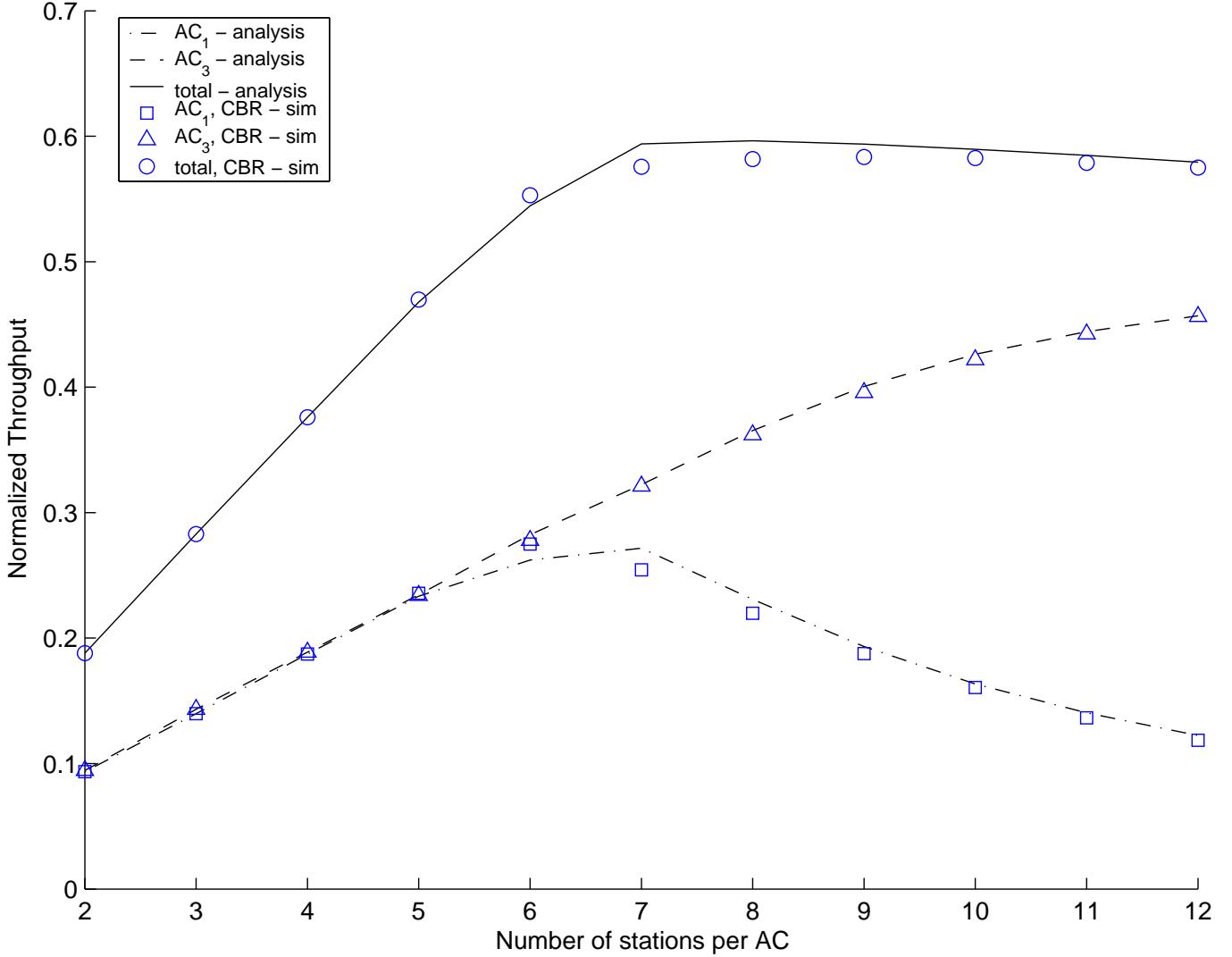


Fig. 9. Normalized throughput prediction of the proposed model for 2 AC heterogeneous scenario with respect to increasing number of stations when MAC buffer size is 10 packets and total offered load per AC is 2 Mbps ($TXOP_3 = 1504ms$, $TXOP_1 = 3008ms$). Simulation results are also added for the scenario when both AC₁ and AC₃ uses CBR traffic.

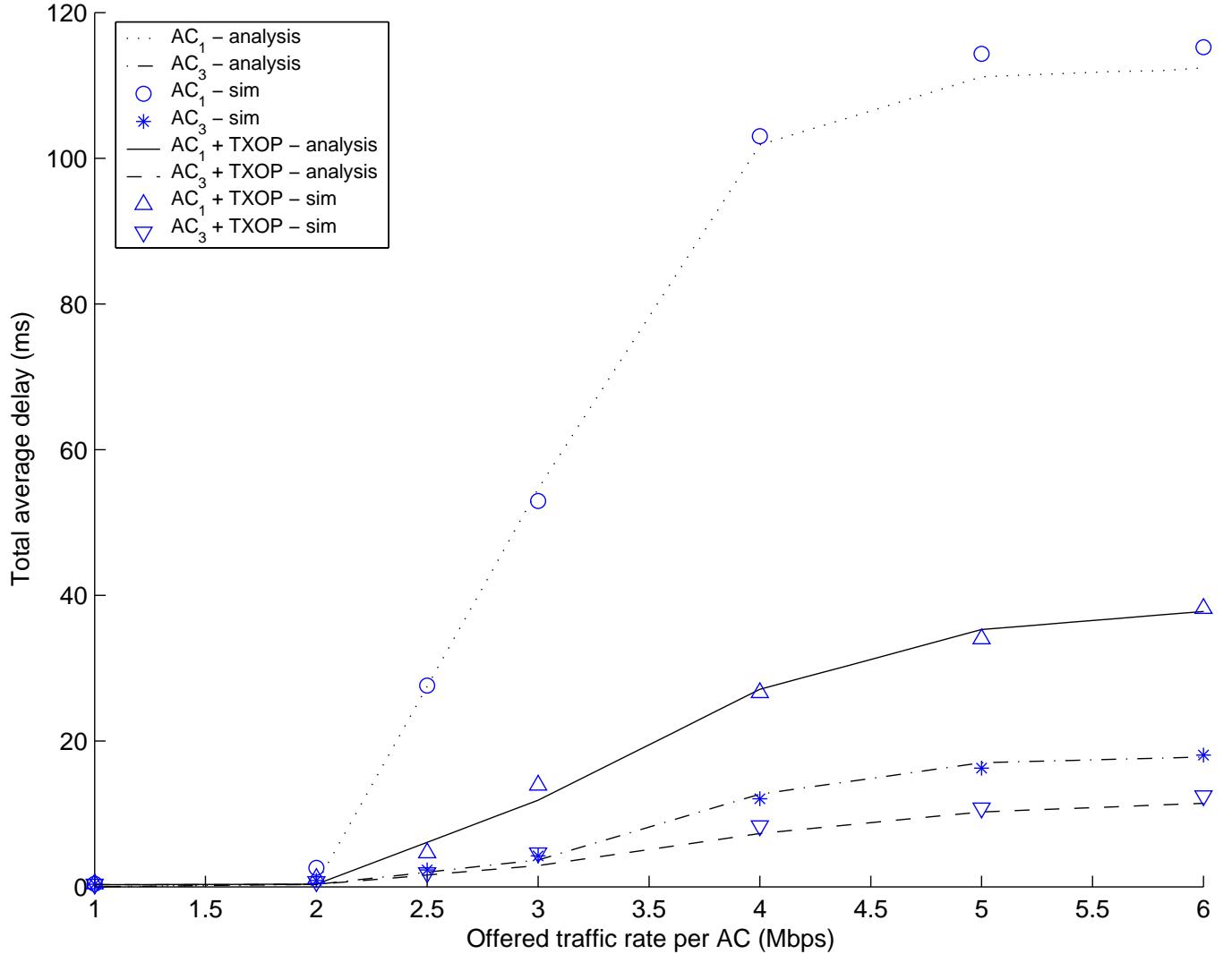


Fig. 10. Total average delay prediction of the proposed model for 2 AC heterogeneous scenario with respect to increasing load per AC at each station. In the first scenario, TXOP limits are set to 0 ms for both ACs. In the second scenario, TXOP limits are set to 1.504 ms and 3.008 ms for high and low priority ACs respectively. Simulation results are also added for comparison.

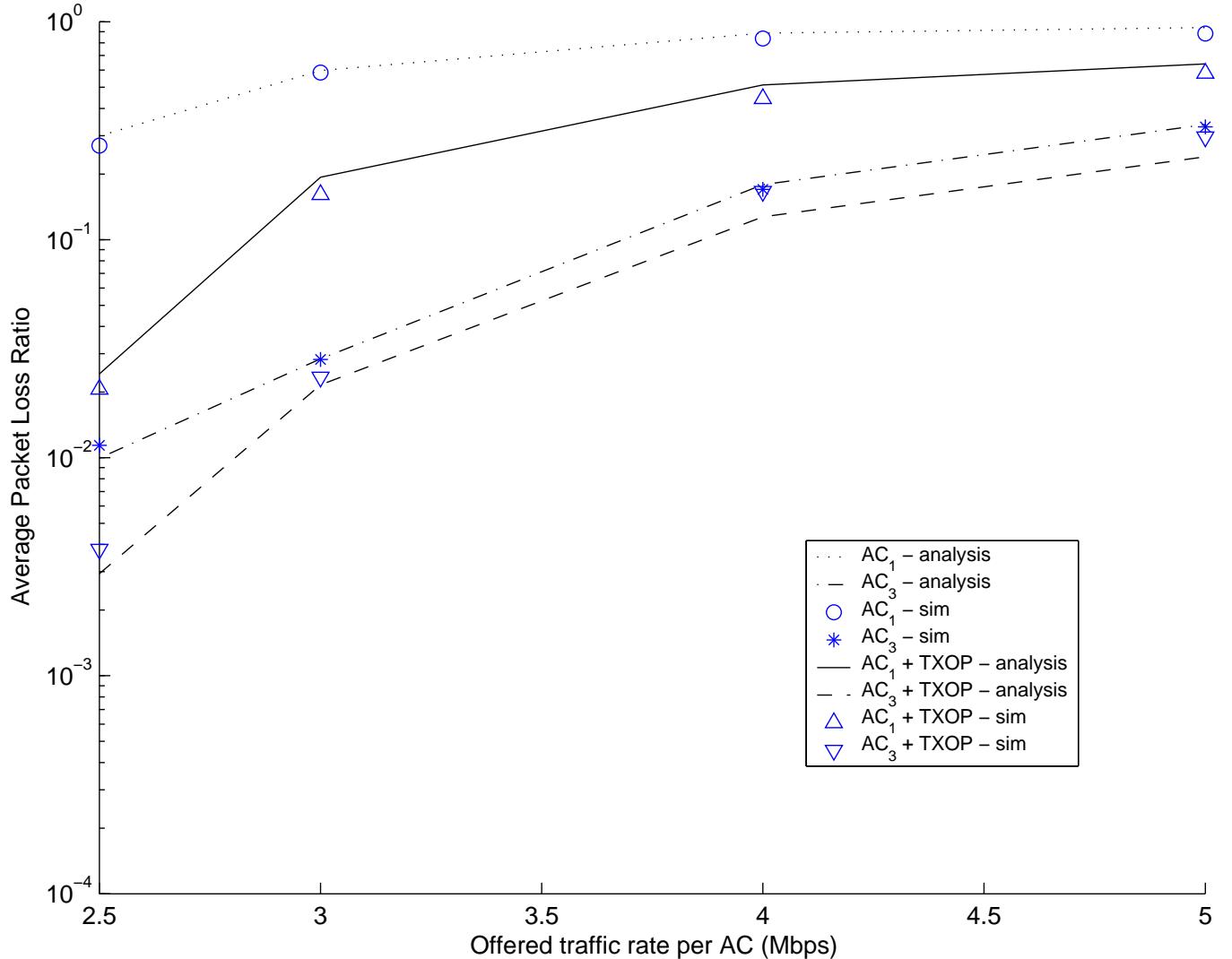


Fig. 11. Average packet loss ratio prediction of the proposed model for 2 AC heterogeneous scenario with respect to increasing load per AC at each station. In the first scenario, TXOP limits are set to 0 ms for both ACs. In the second scenario, TXOP limits are set to 1.504 ms and 3.008 ms for high and low priority ACs respectively. Simulation results are also added for comparison.